

The Virgo High-Resolution CO Survey I. – CO Atlas –

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Abstract

We present the results of the Virgo high-resolution CO survey (ViCS) obtained with the Nobeyama Millimeter-wave Array (NMA). This survey was made in the course of a long-term project at Nobeyama from 1999 December through 2002 April. The objects were selected from Virgo cluster members, considering CO richness from single dish flux, mild inclination, and lack of strong tidal perturbations. The central $1'$ regions (~ 4.7 kpc) of 15 spiral galaxies were observed with resolutions of $2-5''$ and $10-20$ km s⁻¹, and sensitivities of ~ 20 mJy beam⁻¹ for a 10 km s⁻¹ channel. The objects lie at the same distance of the Virgo cluster (16.1 Mpc), which is advantageous for comparisons among individual galaxies. We describe the details of observations and data reduction, and present an atlas of integrated CO intensity maps, velocity fields and position-velocity diagrams along the major axes. The molecular gas morphology in the Virgo galaxies shows a wealth of variety, not specifically depending on the Hubble types. Several galaxies show strong concentration of gas in the central few kpc region, where the CO morphology shows either "single-peak" or "twin-peaks". Morphology of more extended CO components can be classified into "arm-type", "bar-type", and "amorphous-type".

Key Words : galaxies: spiral — galaxies: ISM — galaxies: structure — galaxies: Virgo

1 Introduction

CO-line observations play an essential role in studying the kinematics and interstellar physics in the central regions of spiral galaxies, where the interstellar matter is mostly in the molecular-gas phase and is strongly concentrated (Sofue et al. 1995; Honma et al. 1995). There have been numerous observations of

nearby galaxies in the CO line emissions with single dish telescopes (Young & Scoville 1991; Braine et al. 1993; Young et al. 1995; Nishiyama & Nakai 2001). Large-scale CO line surveys of the Virgo galaxies have been obtained using the FCRAO 14-m telescope at an angular resolution of $45''$ by Kenney & Young (1988), and the BTL 7-m telescope by Stark et al. (1986). These surveys with single dishes were made with angular resolutions of tens of arcsec, and have given information about the global structure of molecular disks in Virgo and nearby galaxies.

Interferometer observations at high angular resolutions are crucial for studying detailed molecular disk structures within the central few hundred parsecs (Sargent & Welch 1993). High-spectral resolution is also crucial to investigate the detailed kinematics of the central gas disks. Both high spatial and high spectral resolutions provide us with precise velocity fields and rotation curves, which are the basis for deriving the fundamental parameters such as the mass distribution, bars and related shock phenomena, triggering mechanism of starburst and/or fueling mechanism of massive black holes. Interferometer observations have often performed to investigate the individuality of each galactic center and activity. Recently, some large surveys of nearby galaxies have started to be reported.

The Nobeyama mm-wave Array (NMA) and Owens Valley Radio Observatory (OVRO) mm-wave array were used since 1990's to map the central regions of nearby spiral galaxies with the CO line at a typical angular resolution of $4''$ (Sakamoto et al. 1999a). The Berkely-Illinois-Maryland Association Survey of Nearby Galaxies (BIMA SONG) has mapped 44 nearby galaxies at typical resolutions of $6''$ (Regan et al. 2001). Interferometer observations of several nearby galaxies have been also conducted from various interests, such as bars (e.g., Kenney et al. 1992; Regan et al. 1999),

star formation (e.g., Wong & Blitz 2002), and nuclear activity (e.g., Baker 1999; Sakamoto et al. 1999a; Kohno et al. 1999; Schinnerer et al. 1999).

The ViCS (Virgo high-resolution CO survey) project with the NMA has been performed in order to obtain a homogeneous high angular- and spectral-resolution database for a large number of CO-bright Virgo Cluster spirals in the $^{12}\text{CO}(J = 1 - 0)$ line. Angular resolutions were $\sim 3''$ after reduction in the conventional CLEAN procedure with natural weighting. The major scientific motivation was to investigate the detailed central kinematics of the galaxies, particularly the innermost rotation curves from analyses of position-velocity diagrams across the nuclei, which would be effective to detect central compact massive objects. The data are also useful for investigation of the kinematics and ISM physics of the central molecular disks, and their environmental effect in the cluster circumstance.

An advantage to observe the Virgo Cluster galaxies is their almost identical distance, which has been accurately determined to be 16.1 Mpc ($1''$ corresponds to 78 pc) by the Cepheid calibrations (Ferrarese et al. 1996). Since our target galaxies lie within 2 Mpc from the Virgo center, M87, the distance ambiguity will be at most 15%, mostly less than 10%. The accurate distance will enable us to estimate physical quantities rather precisely, such as the CO and dynamical masses, and linear scales of gas disks.

The ViCS results will be published in a series of papers. In this paper we describe the overall observations and reduction, and present an atlas of the central molecular disks of Virgo galaxies. In the forthcoming papers we will describe more details of the observations, analyses, and results for individual galaxies, as well as rotation curves and central kinematics, investigations of the ISM physics, and comparison with other wavelengths observations. The database will be opened for public use on our web page.

2 Observations and Reduction

2.1 Target Galaxies

The target galaxies in the survey have been selected from the list of spiral galaxies of the FCRAO CO-line survey by Kenney & Young (1988) by the following criteria.

1. The sources were chosen in the order of CO line peak antenna temperatures $T_A^*(\text{peak})$ at the optical centers. Twenty-eight galaxies with the peak antenna temperatures above 20 mK were selected from 42 galaxies of Kenney & Young (1988).
2. Inclination angles were limited to be $25^\circ \leq i \leq 75^\circ$ in order to investigate central gas dynamics. This criterion excluded NGC 4293 ($i = 76^\circ$), NGC 4302

($i = 90^\circ$), NGC 4312 ($i = 78^\circ$), and NGC 4710 ($i = 90^\circ$).

3. Galaxies with morphological type of S0, i.e. NGC 4293, NGC 4710 and NGC 4438, were excluded.
4. Interacting galaxies were excluded by a criterion that the galaxies have no companion within $8'$ radius. Pairs of NGC 4568/4567, NGC 4298/4302, and NGC 4647 were excluded.
5. Peculiar galaxies in optical images, i.e. NGC 4438 and NGC 4064, were excluded.
6. Galaxies observed with the NMA since 1994 were excluded. NGC 4321 and NGC 4527 have been observed by Sakamoto et al. (1995) and Sofue et al. (1999), respectively.

Sixteen galaxies were selected on the basis of these criteria, and we have observed 15 galaxies except NGC 4450. The targets are listed in Table 1, which also summarizes the morphological type, B-band total magnitude, optical size, inclination, position angle from optical isophotal contours, and nuclear activity from optical spectroscopy (Ho et al. 1997a,b). The table list also the CO-line peak temperature, integrated intensity, intensity-weighted mean velocity, and velocity width from the single dish CO-line observations (Kenney & Young 1988),

The selection criterion 1 by the peak antenna temperature was applied because of higher probability of detection in a single channel. We note that the FCRAO survey with $45''$ resolution (Kenney & Young 1988) shows that all galaxies, except one, are centrally CO peaked. Their data show that the peak temperature and maximum CO intensity have approximately a linear correlation, and that the CO scale radius is an increasing function of maximum CO intensity. This implies that our selection by peak temperature is approximately equivalent to a selection by total integrated CO intensity, and hence by total CO luminosity for their equal distances. Hence, our target galaxies, and some that were not selected by the reason that they were already observed by NMA, would represent the most CO luminous Virgo galaxies.

— Table 1 —

2.2 Observations

We have performed aperture synthesis observations of the $^{12}\text{CO}(J = 1 - 0)$ line emission from the 15 Virgo galaxies listed in Table 1 in the course of a long-term project during the winter seasons of 2000 (1999 Dec.-2000 Apr.), 2001 (2000 Dec.-2001 Apr.) and 2002 (2001 Dec.-2002 Apr.). We made the observations in three available configurations: AB (long baselines), C

(medium) and D (short) configurations. The visibility data covered projected baselines from about 10 to 351 m. The NMA consisted of six 10-m antennas, providing a field of view with a FWHP beam width of $65''$ at 115 GHz. Since interferometry observations sample data in a Fourier space, the range of collected Fourier components, or baselines, determines the detectable sizes of objects. In our observations, the antenna size limited the minimum projected baseline length, restricting the largest detectable size to about $54''$. Thus our data may miss some fluxes of extended components of the objects. Table 2 lists the observation periods and array configurations, observed central frequencies, and the positions of pointing centers as well as phase-reference centers for individual galaxies.

— Table 2 —

The antenna were equipped with tuner-less SIS receivers, which had receiver noise temperatures of about 30 K in double sidebands, and the typical system noise temperatures were about 400 K in single sideband. We used a digital spectro-correlator system (Okumura et al. 2000), which had two spectroscopic modes (bandwidth of 512 and 1024 MHz); we used the mode covering 512 MHz (1331 km s^{-1}) with 256 channels and 2 MHz (5.2 km s^{-1}) resolutions.

The nearby radio point source 3C 273 was used as the flux and phase calibrator, which was observed every 20 minutes. The band pass response across the channels was also calibrated using the 3C 273 data. The intrinsic flux density of 3C 273 at the observing frequency was calibrated for each observing run (typically 5 days) using the planets (Mars etc.). The flux of 3C 273 during the three years of observing periods was gradually variable between 9 and 12 Jy. The uncertainty in the absolute flux scale for each observing run was $\sim \pm 15 \%$, which apply to all results presented in this paper.

2.3 Reduction

The raw data were calibrated using UVPROC-II, a first-stage reduction software (Tsutumi et al. 1997), and were Fourier-transformed using the NRAO Astronomical Image Processing System (AIPS). We applied the CLEAN method with natural weighting to obtain three dimensional data cubes (RA, DEC, V_{LSR}). The intensity data were averaged in 2 to 6 bins ($10.4 - 31.2 \text{ km s}^{-1}$) of the original channels in the spectro-correlator, and the channel increments were set to 2 to 4 ($10.4 - 20.8 \text{ km s}^{-1}$). The intensity scale at this stage was in Jy per synthesized beam, which can be converted to brightness temperature in Kelvin. The resultant synthesized beam sizes range in $2 - 5''$. The typical rms noise scaled for a 10 km s^{-1} channel was 20 mJy beam^{-1} . Table 3 lists the resultant parameters

of the data cubes for individual galaxies.

— Table 3 —

In addition to the above reduction parameter set, we CLEANed the data with tapered and uniform weighting functions, which provided low ($\sim 5''$) and high ($\sim 1''$) resolution maps, respectively. We will present those maps in separated papers for discussing individual galaxies.

We calculated the fractions of the recovered single-dish flux from our aperture synthesis observations, which are listed in table 3. We first corrected the data cube for primary beam attenuation, and convolved with a Gaussian single-dish beam of FWHM $45''$ (comparable to that of the FCRAO survey), and took the flux at the pointing center of the FCRAO observations. The recovered fluxes were typically 80%, which recovered almost all fluxes within the field of view.

However, a few galaxies showed exceptionally low and high recovered fluxes. The recovered flux of NGC 4535 was greater than the FCRAO flux by about twice. We made careful analyses of the raw data for several times: We made UV data for C, D, C+D, and AB+C+D array configurations, which were obtained in independent observing periods (Table 2). We, then CLEANed them separately, but obtained about the same flux for all the configurations. Also the rms noises of the reduced cubes and maps are comparable to those for other galaxies observed in the same periods. Hence, we conclude that the flux calibration was correct. The flux disagreement could be possible, if the FCRAO flux was about significantly under-estimated, and ours was about 15% over-estimated, both within the measurement errors. The recovered flux of NGC 4548 was only 16% of the FCRAO flux. This may have happened due to larger sizes of the missing components than the maximum detectable size of our observations (§2.2). Alternatively, it could be due to very low brightness of the extended components. In fact, the FCRAO flux is as weak as 6.7 K km s^{-1} with $45''$ beam. If the rest 84% is extended in the $45''$ beam, the intensity for our beam ($2''.6 \times 2''.0$) would be 5.6 K km s^{-1} . For an assumed line width of about 20 km s^{-1} in our beam, the expected brightness is only 30 mK, which is much below our detection limit.

We have checked for continuum sources in the galaxies by making channel maps for a wide range of velocity. The channel maps for individual galaxies are shown in figure A1 in the Appendix, where the outermost channels can be used to check continuum fluxes. As figure A1 shows, no significant continuum source has been detected in any of the observed galaxies by the present sensitivity, which is typically 20 mJy beam^{-1} in rms noise as listed in table 3. Nevertheless, such galaxy as NGC 4579, which contains an AGN, could have some continuum emission. So, we applied deeper

continuum checking for this galaxy. We CLEANed the $2 \text{ MHz} \times 256$ -channel data cube of NGC 4579 by binning every 32 channels (168 km/s). However, no continuum source stronger than 10 mJy was found in the outermost-velocity channels ($\pm \sim 500 \text{ km s}^{-1}$), where no CO line emission is expected.

3 The CO Atlas of Virgo Spirals

3.1 CO Intensity Maps

Figure 1 (top-left panels) shows optical ‘looks’ of the observed galaxies for a $5' \times 5'$ area taken from the STScI Digitized Sky Survey (DSS) second generation blue images. The inserted squares show areas for the CO maps. We present total integrated intensity maps of the CO emission in the bottom left panel. The intensity maps were obtained by using the AIPS task ‘MOMNT’, which integrated the intensities by velocity only when the intensity exceeds a threshold level. The threshold level was taken to be 2 to 3 times the rms noise in the data cube. Channel maps of the observed galaxies are shown in Appendix, and will be discussed in more detail in the forthcoming papers of this series on individual galaxies.

The bottom-right panel shows intensity-weighted velocity fields for the $1' \times 1'$ regions (our field of view is $65''$ at FWHP at 115 GHz), and the top-right panels show position-velocity diagrams along the major axes (top right), except for NGC 4254 and NGC 4402, for which $80'' \times 80''$ regions are shown.

The primary-beam correction has not been applied in these maps. The intensity scales in the maps are in Kelvin of brightness temperature, rather than in Jy beam^{-1} scale that is directly derived from interferometer observations, for convenience to compare with single dish observations and to convert to the molecular hydrogen column density. We measured the peak CO intensities using these maps and listed in table 5 together with the CO peak brightness temperatures as read from the data cubes.

— Table 5 —

Figure 2 shows the CO intensity maps in the same angular and linear scales. Each box covers a $1' \times 1'$ region, which corresponds to $4.7 \text{ kpc} \times 4.7 \text{ kpc}$ region for an assumed Virgo distance of 16.1 Mpc (Ferrarese et al. 1996). Figure 3 shows velocity fields corresponding to figure 2. In figure 4 we plot the CO intensity maps in the same angular scale on the Virgo Cluster region, where each map scale has been enlarged by 50 times the real angular size.

— Fig. 1 —

— Fig. 2 —

— Fig. 3 —

— Fig. 4 —

3.2 Velocity Fields

Figure 1 (bottom left panels) shows intensity-weighted velocity fields for the observed $1' \times 1'$ regions, which are the same regions for the integrated-intensity maps at the bottom right panels. For NGC 4254 and NGC 4402, the $80'' \times 80''$ regions are presented. Figure 3 shows the velocity fields in the same angular scales. The general pattern of the velocity field in figures 1 and 3 is a symmetric spider diagram, indicating a regular circular rotation of the CO disk. Slight non-circular streaming motions, such as due to spiral arms and bars, are superposed on the regular rotation. However, there are some galaxies that show strong non-circular motion; NGC 4569 has an extremely large deviation from the circular rotation, indicating either high-velocity streaming or a large-amplitude warping in the central disk.

3.3 Position-Velocity (PV) diagrams

Position-velocity (PV) diagrams are shown in figure 1 (top right). These diagrams were made by slicing the data cubes along the optical major axes with appropriate widths for individual galaxies. Most galaxies have steeply rising rotation velocity in the central 100 to 200 pc radii. Such sudden rise of rotation velocity in the close vicinity of the nuclei had not been clearly detected in the lower-resolution observations. One of the major purposes of the present CO survey was to obtain the central rotation curves to investigate possible central massive cores, which have been found in many nearby galaxies (Sofue et al. 1999; Takamiya & Sofue 2000; Sofue and Rubin 2001; Sofue et al 2001; Koda et al 2002). In a separated paper (Sofue et al. 2003a), we describe the result of detailed analyses of the PV diagrams and derivation of accurate rotation curves by applying a new iteration method (Takamiya & Sofue 2002), and discuss the central mass distribution.

3.4 Uni-scale Atlas of CO Intensities

In order to give an overview on the general characteristics of distributions of the molecular gas (CO intensity) in the observed galaxies, it is helpful to compare the galaxies in a unified scheme. In figure 2, we present the observed I_{CO} distributions in the same angular and intensity scales. The image sizes are all $1.0' \times 1.0'$, corresponding to $4.68 \text{ kpc} \times 4.68 \text{ kpc}$ for an assumed distance of 16.1 Mpc . The contours are drawn at the same levels of 5, 10, 20, 40, 80, 160 K km s^{-1} for all galaxies.

3.5 Uni-scale Atlas of Velocity Fields

Figure 3 shows the same as Figure 2, but for distributions of intensity weighted velocities. The velocity fields generally show a ‘spider diagram’ pattern, indicating circular rotation of the molecular disk. The rotation velocity rises rapidly in the central few hundred parsecs, which is more clearly observed in the position-velocity diagrams in figure 1. In many galaxies, the spider diagrams are more or less distorted, indicating either non-circular streaming motion or warping of the gas disk.

3.6 Sky Plot of CO Maps on the Virgo Cluster region

In figure 4 we plot the I_{CO} maps on the sky area of the Virgo Cluster in a similar manner to a plot of HI maps by Cayatte et al. (1990). The angular scales are enlarged by a factor of 50 for individual galaxies. The CO distributions appear to be not strongly correlated with the distance from the center of the Cluster at M87, which is marked by a cross. This property is very different from the HI gas distribution; The HI disks of inner-cluster galaxies are usually largely distorted and are often truncated by the ram-pressure of the intracluster medium (Cayatte et al. 1990), while the central CO disks are not strongly perturbed by the ambient gas in the cluster, probably because they lie deep in their galactic potentials.

3.7 The ViCS Data Base

The calibrated and reduced data presented in this paper will be opened on our web page in the form of FITS formatted cubes and maps, and in gif-formatted images at the URL, <http://www.iaa.s.u-tokyo.ac.jp/radio/virgo/>.

4 Central Positions and CO Distributions

4.1 Central Positions

In order to determine the central positions, we fitted a disk model with a Brandt-type rotation curve (Brandt 1965) to intensity-weighted velocity fields using the AIPS task GAL. Since this task assumes a pure circular rotation, we used only central several arcseconds for the fitting, out of which the isovelocity contours indicate some deviations from circular rotation. The iteration in the task could occasionally provide different results with different initial guesses. We checked this error by changing the initial guess in appropriate ranges, and confirmed that the task suffices to provide the dynamical centers accurate to about $1''$ in most

cases. The derived central positions are listed in Table 4.

The thus obtained center positions were in coincident with the NED center positions within an arcsecond in most cases. However, in such cases that the central CO distribution is not smooth, or the velocity field is strongly perturbed, and hence above dynamical centers are not reliable, we determined the central positions from the literature. The center of NGC 4212, which shows patchy CO distribution (Figure 1), was adopted from the optical observations by Cotton et al. (1999), which coincides with our CO emission peak within an error of $\sim 1''$. NGC 4569 shows strong noncircular motions in the velocity field and position-velocity diagram; we adopted the central position determined by Sakamoto et al. (1999) from their CO interferometry observations with a lower resolution. The center of NGC 4579 was taken to coincide with the position of the unresolved radio continuum source (Ho and Ulvestad 2001).

— Table 4 —

4.2 Radial Distribution of CO gas

Figure 5 displays azimuthally averaged radial profiles of CO-line intensities in unit of K km s^{-1} as projected on the galaxies’ disks corrected for the inclinations. In order to make these plots, integrated-intensity maps without clipping were corrected for the primary beam attenuation, and we applied the AIPS task IIRING around the central positions derived in §4.1. We fixed the inclination and position angles for each galaxy to those provided from optical observations (Table 1).

The sampling intervals in the plots were set to be $0''.5$. However, the effective sampling intervals are equal to the beam widths. The number of effective sampling points for the fit increases with radius r proportionally to r , and hence the statistical error decreases proportionally to $r^{-1/2}$. The intensity error at each point in a map is given by $\Delta I = \Delta T \times N_c^{1/2} \times \Delta V$ ($\sim 15 \text{ K km s}^{-1}$), where ΔT ($\sim 0.3 \text{ K}$), N_c (~ 25), and ΔV ($\sim 10 \text{ km s}^{-1}$) are the rms, number of channels within the expected velocity width, and the velocity interval, respectively, as given in table 3. Therefore, the typical error of the profiles is given approximately by $\sim 15(r/\text{beam width})^{-1/2} \text{ K km s}^{-1}$.

— Fig. 5 —

The intensity distributions in the central 10 to $15''$ regions are approximately exponential with scale radii 5 to $10''$, or 400 to 800 pc. These scale radii are a few times smaller than those derived by Regan et al. (2001). Since our survey has three times higher resolution ($2''$) than theirs ($6''$), we may detect the central cusps of the CO distributions. In most cases, the outer regions than $20''$ are not significantly detected, except

for some cases with disk components. Three of our target galaxies, NGC 4254, 4501 and 4569, have been observed in CO line with lower sensitivity and resolutions (Sakamoto et al. 1999). Our radial profiles for NGC 4501 and 4569 are consistent with those from the previous observations. The profile for NGC 4254 is also roughly consistent with the previous result, while there are some small scale deviations.

The ellipse fit gives a quantitative presentation of the radial profiles including the outskirts. However, the fit loses linear resolution, depending strongly on the inclination, because it uses the data in the minor axis direction with an equal weight. Figure 5 shows that many galaxies have a strong concentration of CO gas within the central $10''$ (0.8 kpc) radius, while some have a plateau or a dip at the center. We discuss such galaxies in §5 as a central-/single-peak and twin-peaks types, respectively.

5 Molecular gas morphology

The molecular gas distributions show a wealth of variety. Although it is difficult to categorize them in a simple way, we can find some characteristic types in the central gas distributions. Many galaxies have high concentration of CO gas in the central a few kpc region, where the CO morphology shows either single peak or twin peaks. More extended components have more variety of morphologies, which can be classified into arm type, bar type, and amorphous type.

5.1 Central gas distributions

1. Central peak and/or Single peak: Many galaxies show strong concentration of molecular gas around the nuclei in so far as the present maps are concerned. NGC 4212, NGC 4419, NGC 4501, NGC 4535, and NGC 4536 are the examples. The typical size of these central peaks is about 200 - 400 pc. In most cases, their peaks are single at the present resolution, which we call "single peak". Figure 6 shows the CO intensity distributions in the central $20'' \times 20''$ regions (1.6 kpc square) of the central-/single-peak galaxies. The central/single peak galaxies shares a considerable fraction among the observed galaxies. Note that the object selection was made by peak antenna temperature in the FCRAO survey with a $45''$ beam. Hence, the present maps could have a selection effect for galaxies with higher peak-temperatures. However, as argued in §2, our object selection is approximately equivalent to a selection by CO luminosity. We may consider that the statistics with the presently observed galaxies is significant to discuss the general types of central CO morphology of the most CO luminous Virgo galaxies.

2. Twin peaks: Typical example of twin-peak molecular gas distribution is seen for NGC 4303, which shows two offset open molecular arms along the optical bar, which end at a molecular ring with two peaks. Kenney et al. (1992) have reported both single-peak, and twin-peaks types. They selected four barred galaxies with strong CO and FIR emission, and showed that the barred galaxies have twin peaks in CO likely as the consequence of bar-induced inflow. In so far as the present data set is concerned, which includes galaxies of random types with the CO emission concentrated in the central $45''$ (3.5 kpc) regions, twin-peak galaxies shares rather a small fraction.

Kenney et al. (1992) showed that the separations between twin peaks are about 200 - 400 pc, while our single peak galaxies do not have double peaks even in the same scale ($3'' \sim 200$ pc). Note, however, that this classification may depend on the spatial resolution; it may happen that a single peak at our resolution consists of a more number of inner structures at higher resolution. In fact, NGC 4501 appears to be a single peak type in the present atlas, while a higher resolution image show a small patchy ring with a diameter of $\sim 3''$ (Onodera et al. 2003; private communication).

PV diagrams may apparently imply spatially-unresolved double peaks with separated velocities. However, a single peak galaxy may apparently show two peaks on a PV diagram, at the positive and negative terminal velocity ends at turnover radii of central rising and outer flat rotation curves, even when the gas distribution has no spatially-separated double peaks (Sofue et al. 1999; Sakamoto et al. 1999a). Hence, PV diagrams may not be used for the spatial morphological classification.

6 Description of Individual Galaxies

We describe individual galaxies about their CO properties obtained from the present observations.

6.1 NGC 4192

An extremely bright CO peak is observed at the center, which classifies this galaxy in a "central-peak" type, while it appears that the peak may be resolved into two peaks at higher resolution. Hence, the classification depends on the resolution. The central peak is surrounded by a bright disk at high inclination at about the same inclination as the optical disk. The position-velocity diagram shows a very high-velocity rotation, whose maximum reaches almost 250 km s^{-1} . However,

the central CO peak is rotating more slowly at about 100 km s^{-1} .

6.2 NGC 4212

The CO distribution consists of a molecular core and extended straight arms in the direction of the major axis. The core is shifted from the map center toward the NE by a few arcseconds. The velocity field and PV diagram indicate that the rotation is rigid body-like, while the core shows a steeper velocity gradient.

6.3 NGC 4254

The central molecular gas distribution shows a bar-like elongation, while no optical bar feature is seen in the visual-band images. The CO intensity has a slight depression at the dynamical center, which coincides with the nucleus. Two well-developed spiral arms wind out from the bar ends toward the south and north. The south-eastern arm bifurcates into a tightly-wound dense molecular arm with an almost zero pitch angle. Hence, the molecular disk has three arms, and the arms are well correlated with optical dark lanes. The velocity field shows a regular spider pattern, indicating a circular rotation of the disk, on which small-amplitude streaming motion due to the spiral arms are superposed. The PV diagram shows a sharp rise in the central few arcseconds, indicating a massive core, and then the velocity increases gradually. Overall distributions and kinematics agree with the previous low resolution observations (Sakamoto et al. 1999a). A detailed study of this galaxy with consideration of the ram-pressure effect by the intra-cluster medium is presented in Sofue et al. (2003b).

6.4 NGC 4303

CO gas is highly concentrated in the nuclear disk within a radius $r \sim 8''$ (600 pc). The nuclear disk comprises the "twin peaks" at the eastern and western edges of the nuclear disk, and there appears to exist a diffuse central component around the nucleus between the twin peaks. Two prominent bisymmetric spiral arms, or offset ridges, wind out from these twin peaks, and extend toward the north and south along the dark lanes in the optical bar. The PV diagram along the major axis (north-south) indicates a rise of rotation velocity within $r \sim 2''$ (160 pc) to $160 - 180 \text{ km s}^{-1}$. Our result is consistent with the high-resolution observations with the OVRO interferometer by Schinnerer et al. (2002). Detailed description of this galaxy are given in a separate paper of this series by Koda et al. (2003: private communication).

6.5 NGC 4402

The CO intensity distribution shows a high density nuclear molecular disk of $r \sim 10''$. The nuclear disk is surrounded by a more extended molecular disk of radius $\sim 30''$ (2 kpc). This outer disk appears to be consisting of two spiral arms, one extends to the west from the southern edge of the nuclear disk, tracing the dark lane, and the other arm toward the east from the north-eastern edge of the nuclear disk. The velocity field shows a usual spider diagram superposed by some streaming motion in the molecular ring/arms. The PV diagram shows a nuclear component and outer ring/arms.

6.6 NGC 4419

The CO gas is strongly concentrated in the central $5''$ radius disk, which is associated with an elongated outer disk component. Kenney et al. (1990) also reported the concentrated CO distribution. The outer molecular disk is lopsided toward the north-west. The PV diagram indicates that the central component has a rotation velocity as high as 150 km s^{-1} within $5''$ radius, which is followed by a gradually rising disk rotation.

6.7 NGC 4501

A nuclear concentration of the molecular gas of radius $3''$ is remarkable, as reported by Sakamoto et al. (1999a). This is classified as the "single-peak" type, although the peak intensity is not particularly high compared with the other typical single peaks. This central peak is surrounded by an extended component elongated in the SE to NW direction, with the SE end at $5''$ radius being brighter. Two prominent molecular arms are running at $r \sim 20''$. The north-eastern arm is much stronger than the south-western arm. Both arms are associated with the dark lanes along the optical spiral arms. The velocity field and PV diagram indicate sharp rise of rotation velocity in the nuclear disk. Detailed description and modeling by spiral-shock accretion mechanism are given in Onodera et al. (2003: private communication).

6.8 NGC 4535

The molecular gas shows a strong concentration in the central region of $\sim 6''$ radius. This galaxy is a typical "single-peak" type. Offset bars are extending from the central disk toward the NE and SW, coinciding with the optical dark lanes in the bar. The velocity field shows a usual spider diagram with the zero velocity node at position angle of 90° , coinciding with the optical minor axis. However, the CO arms along the dark lanes show some non-circular streaming velocity, indicating inflow along the arms. The PV diagram

shows a sharply rising, but rigid body-like behavior within the central molecular disk.

6.9 NGC 4536

This is also a typical "single-peak" type galaxy with the molecular gas being concentrated in the nuclear disk of $\sim 10''$ radius and an unresolved compact core exists at the nucleus. The velocity field shows a spider diagram, and the PV diagram indicates that the rotation velocity rises to 200 km s^{-1} within the central $2''$. There appears no strong non-circular streaming motion.

6.10 NGC 4548

This is a typical barred galaxy. CO emission is very weak compared with the other galaxies. The CO distribution is highly concentrated near the nucleus, being centrally peaked, and no extended emission is detected. The recovered flux is only 16% of the FCRAO flux with 45beam (§2.3), and the rest 84% (5.6 K km s^{-1}) could be due to very extended components with sizes greater than our maximum detectable size ($54''$).

6.11 NGC 4569

The molecular gas is highly concentrated within $\sim 1 \text{ kpc}$ radius. The CO intensity distribution is elongated in the same direction as the optical major axis, and has two peaks with depression at the nucleus, consistent with the earlier CO map (Sakamoto et al. 1999a). Thus, the central molecular morphology of this galaxy may be classified in twin peaks at the present resolution. However, a higher resolution CO map reveals that the apparent two peaks coincide with both ends of an elliptical molecular ring, while they are not associated with so called offset ridges (Nakanishi et al. 2003). The velocity field is strongly disturbed from circular rotation, and the PV diagram indicates significant 'forbidden' velocities. Nakanishi et al. (2003) discuss the kinematics of this galaxy in detail, and tried to explain these features using two models of non-circular motion and warping of the inner disk. And they conclude that it is natural that disturbed velocity field and forbidden velocities of the PV diagram are due to non-circular motion. Helfer et al. (2001) have reported an extended CO emission from their wide-field mosaic image. Jogee et al. (2001) have also presented a high resolution CO image of this galaxy.

6.12 NGC 4571

No significant detection of the CO line was obtained for this galaxy, not only in channel maps, but also in an integrated-intensity map. Our resultant rms was 11.5 K km s^{-1} for a 130 km s^{-1} width, that is greater

than 3.3 K km s^{-1} from single dish observations (Table 1). Since the map shows only noises, we do not present the result.

6.13 NGC 4579

The CO distribution is elongated in the east-west direction, about 30 deg displaced from the optical bar axis. There are two major CO peaks with asymmetric peak intensities, which are associated with symmetric spiral features as reported by Kohno et al. (1999). The velocity field shows a higher rotation velocity than 200 km s^{-1} in the central few arcseconds, which is more clearly visible in the position-velocity diagram.

6.14 NGC 4654

This galaxy is known for its lopsided structure in the optical as well HI disks, most likely due to the ram-pressure effect of the intracluster gas, blowing from the northwest (Phookun and Mundy 1995). The CO distribution is also lopsided, in the same direction as that of the HI and optical image tail. The lopsided CO distribution suggests that the ram pressure effect is not negligible even in such a central molecular disk. Moreover, the CO distribution is more elongated than the optical/HI disks. The velocity structure is rigid-body like with mildly increasing rotation velocity with the radius. Such rotation characteristics is exceptional among the presently observed PVDs.

6.15 NGC 4689

Like the optical spiral arm features, the CO intensity distribution is amorphous, and is patchy and widely extended. There appears neither spiral arms nor bars in CO, and no central peaks are found. The peak I_{CO} amounts only to $\sim 24 \text{ K km s}^{-1}$, the lowest among the observed galaxies. The velocity field indicates a regular rotation pattern, but the central rise of rotation velocity is mild, as indicated by the PV diagram.

7 Summary and Discussion

We have obtained high-resolution CO-line survey of 15 Virgo spiral galaxies using the Nobeyama Millimeter-wave Array in AB, C and D configurations, and presented the result in the forms of integrated intensities, velocity fields and position-velocity diagrams along the major axes. The galaxies were sampled from the CO brightest galaxies in the Kenney and Young's (1988) list without any bias. The CO properties may be compared with each other without ambiguity of the linear scale, as the distance to the Virgo cluster galaxies are safely taken to be 16.1 Mpc from the Cepheid calibration (Ferrarese et al. 1996). For the homogeneity,

our data will be useful for investigating correlation between the CO properties and other characteristics. We will discuss the correlation of the central peaked CO distributions and nuclear activities in a forthcoming paper of this series. In the second paper of this series, we will derive exact rotation curves by analyzing the position-velocity diagrams, and discuss the dynamical properties of the central regions of the Virgo galaxies, as well as detailed mass distributions.

We summarize the results obtained in this paper as follows, and discuss the implications below. The mean radial profiles of the molecular gas distribution in the inner 10 to 15'' radius regions are approximately exponential with e -folding scale radius of 400 to 700 pc. In some galaxies, more extended disk components are detected, whose scale radii are greater, while the present interferometry data are not appropriate to determine the disk radii precisely.

A careful inspection of the intensity maps shows that the observed intensity distributions have a variety of types, which may be classified into the following types. The centrally concentrated components can be classified into two types: the central-peak or single-peak type and twin peaks type. The latter shows plateau-like radial profiles near the center. The distributions of more extended components can be classified into spiral arms, bars, and amorphous types. It is of particular interest to consider what causes the variety of molecular gas morphology, as it could be intimately related to the activities in the centers of galaxies.

Twin-peaks of molecular gas at the ends of a set of two bisymmetric offset molecular bars (dark lanes) along the optical bar have been noticed for several barred galaxies in relation to fueling mechanisms of interstellar gas toward the central regions (Kenney et al. 1992; Sakamoto et al. 1999a). NGC 4303 is a typical case for the twin-peaks type, and the structure is well explained by a bar-potential and galactic shock hypothesis (Schinnerer et al 2002; Koda et al 2003; private communication). However, the fraction of galaxies having "twin-peaks" is not particularly high in so far as the present resolution maps (2 – 4'' or 150 - 300 pc) are concerned.

On the other hand, "central-" or "single-peak" galaxies share a larger fraction: five galaxies among the fifteen in the present survey at our resolution. Examples are NGC 4192 (SAB(s)ab), NGC 4419 (SB(s)a), NGC 4501 (SA(rs)b), NGC 4535 (SAB(s)c) and NGC 4536 (SAB(rs)bc).

Twin-peaks are often thought to be a consequence of characteristic gaseous orbits in a bar potential: x1 and x2-orbits in a bar intersect each other at the inner ILR, causing collision of the gas at the two intersecting points, and consequently producing twin peaks. Although this simple interpretation of the twin-peaks is attractive, the current study has shown that the single-peak is more popular than the twin-peaks. It is an

interesting subject to consider the origin of the single-peak, while we need a more careful simulation and gas dynamics. We here try to speculate a possible mechanism.

First of all, the twin-peaks are not the final and stable structure of the gas distribution in a bar. The self-gravity of the gas will cause a collapse in the gas structures, particularly such large clumps as twin-peaks will be gravitationally unstable, and cause further infall of gas into the center due to the friction among the clouds (Wada & Habe 1992). Moreover, if there exists central massive object, the friction due to stronger shearing motion will accelerate the accretion toward the nucleus (Fukuda et al. 1998). In fact, most of the galaxies show very steep rise of rotation curve in the central ~ 100 pc region, indicating the existence of massive compact cores of mass $10^8 - 10^9 M_\odot$ around the nuclei (Sofue et al. 2003a). Hence the central single-peak may be formed after the twin-peaks have developed.

The above mechanism could work even if a galaxy shows no prominent bar in the optical/infrared photographs, because even a very weak bisymmetric distortion of a disk potential can cause non-circular motion of gas (Koda & Wada 2003). Also, Onodera et al. (2003: private communication) discuss another possible mechanism to produce a central single-peak by stellar spiral arms for the case of NGC 4501, which indeed has no bar, but shows continuous spiral structure from the disk to the nucleus.

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Table 1: Object List for the High-Resolution Virgo CO Survey (ViCS)

NGC	Morphology	Activity	B_{total} [mag]	Opt. Size [' × ']	i [°]	PA [°]	$T_{\text{MB,peak}}$ [mK]	I_{CO} [K km s ⁻¹]	V_{CO} [km s ⁻¹]	ΔV_{CO} [km s ⁻¹]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
4192	SAB(s)ab	T2	10.95	9.8×2.8	74	155	38	8.9	−105	330
4212	SAC	H	11.83	3.2×1.9	47	75	53	7.5	−60	130
4254	SA(s)c	H	10.44	5.4×4.7	28	45	162	19.3	2407	200
4303	SAB(rs)bc	H	10.18	6.5×5.8	25	0	167	21.6	1555	160
4402	Sb	—	12.55	3.9×1.1	75	90	96	12.4	244	200
4419	SB(s)a	T2	12.08	3.3×1.1	67	133	80	18.5	−203	300
4501	SA(rs)b	S2	10.36	6.9×3.7	58	140	73	21.8	2263	450
4535	SAB(s)c	H	10.59	7.1×5.0	43	0	60	8.5	1949	250
4536	SAB(rs)bc	H	11.16	7.6×3.2	67	116	80	18.4	1793	310
4548	SBb(rs)	L2	10.96	5.4×4.3	37	150	44	6.7	450	210
4569	SAB(rs)ab	T2	10.26	9.5×4.4	63	23	124	26.5	−203	320
4571	SA(r)d	—	11.82	3.6×3.2	38	55	42	3.3	346	130
4579	SAB(rs)b	S1.9/L1.9	10.48	5.9×4.7	37	60	58	7.5	1465	380
4654	SAB(rs)cd	H	11.10	4.9×2.8	52	125	65	6.0	1075	180
4689	SA(rs)bc	H	11.60	4.3×3.5	30	160	51	6.5	1614	210

Notes. — Col.(1): Galaxy name. Col.(2): Morphological type from NED. Col.(3): Nuclear activity from optical spectroscopy (Ho et al. 1997a). H, S, L, and T mean HII, Seyfert, LINER, and Transient-type (HII + LINER), respectively. Cols.(4) and (5) : Total B-band magnitude and apparent sizes along major and minor axes, taken from NED. Col.(6)(7): Inclination and position angle of the major axes taken from Kenney & Young (1988). Cols.(8) and (9): CO Peak temperature and integrated intensity at optical centers taken from the FCRAO survey by Kenney & Young (1988). Scaled to main-beam temperature by a scaling factor of $T_{\text{A}}^*/T_{\text{MB}} = 0.55$ for the FCRAO telescope (Young et al. 1995). Cols.(10) and (11): Intensity-weighted mean velocity and full width at 0 % intensity of CO line from Kenney & Young (1988)

Table 2: Observational Parameters

NGC (1)	Config. (2)	Year (3)	Field Center (4)		Frequency (GHz) (5)	Reference (6)
			RA(J2000)	DEC(J2000)		
4192	AB+C+D	2000-2002	12 13 48.30	+14 54 02.9	115.350000	1
4212	C+D	2000-2001	12 15 39.11	+13 54 04.8	115.286574	2
4254	AB+C+D	2000	12 18 50.03	+14 24 52.8	114.355710	3
4303	AB+C+D	2000	12 21 54.87	+04 28 24.9	114.659250	2
4402	AB+C+D	2001-2002	12 26 07.06	+13 06 45.7	115.200000	1
4419	AB+C+D	2000-2002	12 26 56.43	+15 02 51.1	115.286574	1
4501	AB+C+D	2001-2002	12 31 59.14	+14 25 12.9	114.407000	4
4535	AB+C+D	2000-2001	12 34 20.25	+08 11 52.2	114.507290	5
4536	AB+C+D	2001	12 34 27.07	+02 11 18.3	114.586000	5
4548	AB+C+D	2001	12 35 26.40	+14 29 47.0	115.098000	3
4569	AB+C+D	2000-2002	12 36 49.82	+13 09 45.8	115.286574	4
4571	C+D	2001-2002	12 36 56.40	+14 13 02.0	115.138000	3
4579	AB+C+D	2001-2002	12 37 43.53	+11 49 05.4	114.710000	6
4654	AB+C+D	2000-2002	12 43 55.74	+13 07 44.2	114.811630	1
4689	C+D	2000-2002	12 47 45.60	+13 45 46.0	114.659250	3

Notes. — Col.(1): Galaxy name. Col.(2): NMA configurations used for the observations. Col.(3): Year of the observations. Col.(4): Pointing position as well as the phase tracking center. Col.(5): Observing frequency. Col.(6): References for positions: (1) Condon et al. 1990; (2) Saikia et al. 1994; (3) NED; (4) Sakamoto et al. 1999; (5) Hummel et al. 1987; (6) Kohno et al. 1999

Table 3: Parameters of Cubes

NGC	Synth. Beam			ΔV		N_c	Rms for 10 km s^{-1}		T_b for 1 Jy beam^{-1}	$f_{45''}$	
	(2)			(km s^{-1})			(6)				
	(1)	($''$)	($''$)	($^\circ$)	(3)		(4)	(5)			(mJy/beam)
	(1)	($''$)	($''$)	($^\circ$)	(3)	(4)	(5)	(mJy/beam)	(mK)	(7)	(8)
4192	2.4	1.9	158	20.8	20.8	23	18	363	20.2	47	
4212	4.0	3.7	149	20.8	10.4	22	28	174	6.2	76	
4254	3.0	2.3	148	20.8	10.4	22	25	333	13.3	102	
4303	2.8	1.9	27	10.4	10.4	17	21	363	17.3	97	
4402	2.8	2.3	166	20.8	10.4	20	26	371	14.3	106	
4419	3.5	2.7	159	10.4	10.4	38	26	253	9.7	83	
4501	5.6	3.7	160	10.4	10.4	46	17	75	4.4	85	
4535	3.1	2.6	164	10.4	10.4	23	21	240	11.4	208	
4536	2.5	1.8	173	10.4	10.4	34	17	347	20.4	68	
4548	2.6	2.0	154	31.2	15.6	19	22	389	17.7	16	
4569	4.5	3.1	146	10.4	10.4	37	25	165	6.6	111	
4571	3.8	2.5	154	—	—	0	33	319	9.7	—	
4579	4.5	3.5	152	20.8	10.4	—	22	128	5.8	31	
4654	5.2	3.7	149	20.8	10.4	23	22	105	4.8	142	
4689	5.2	4.2	134	20.4	10.4	17	20	84	4.2	68	

Notes. — Col.(1): Galaxy name. Col.(2): Major and minor axis sizes and position angle for the synthesized beam. Col.(3) and (4): Integrated velocity width of a channel, and sampling width between channels of the cube. Col.(5): Number of channels where emission are detected. Col.(6): Rms noise scaled for a 10 km s^{-1} channel. Col.(7): Equivalent antenna temperature for 1 Jy beam^{-1} . Col.(8): Fraction of single-dish flux recovered by the aperture synthesis observations. Single-dish data are from Kenney & Young (1988).

Table 4: Adopted Parameters for Analyses

NGC (1)	Center Position (2)		Reference (3)
	RA(J2000)	DEC(J2000)	
4192	12 13 48.29	+14 54 01.9	1
4212	12 15 39.40	+13 54 04.6	2
4254	12 18 49.61	+14 24 59.6	1
4303	12 21 54.94	+04 28 25.6	1
4402	12 26 07.45	+13 06 44.7	1
4419	12 26 56.40	+15 02 50.2	1
4501	12 31 59.12	+14 25 13.3	1
4535	12 34 20.35	+08 11 52.2	1
4536	12 34 27.08	+02 11 17.1	1
4548	12 35 26.44	+14 29 47.4	1
4569	12 36 49.82	+13 09 45.8	3
4579	12 37 43.53	+11 49 05.5	4
4654	12 43 56.67	+13 07 36.1	1
4689	12 50 15.86	+13 29 27.4	1

Notes. — Col.(1): Galaxy name. Col.(2): Adopted central position. Col.(3): Reference of the position: (1) This study. Dynamical center derived with the AIPS/GAL package; (2) Cotton et al. 1999; (3) Sakamoto et al. 1999; (4) Ho & Ulvestad 2001.

Table 5: Peak CO Brightness Temperatures and Intensities

NGC	$T_{\text{b,peak}}$ [K]	$I_{\text{CO,peak}}$ [K km s ⁻¹]	$I_{\text{CO,peak}} \times \cos i$ [K km s ⁻¹]
4569	3.54	586	266
4419	5.71	585	229
4536	5.87	575	224
4303	6.48	436	395
4535	5.17	377	275
4192	3.26	348	96
4402	4.06	224	58
4501	1.14	210	111
4548	1.46	123	98
4212	1.38	115	78
4254	3.88	110	97
4579	0.78	84	67
4654	1.15	44	27
4689	0.62	24	21

Each value contains a systematic error of about ± 15 %. Inclination angles from optical isophotos (Table 1) are assumed.

Figure Captions

PS figures are available at <http://www.iao.s.u-tokyo.ac.jp/radio/virgo>

Fig. 1. Atlas of the observed Virgo galaxies. Top top-left panels show DSS second generation blue optical images, each for $5' \times 5'$ area. $^{12}\text{CO}(J=1-0)$ observations were obtained for the central $1' \times 1'$ regions. Bottom panels show observed CO intensity distributions (left) and corresponding velocity fields (center). Position-velocity diagrams along the major axes are shown in the top right panels. Parameters of the galaxies and displayed areas are indicated at the bottom for each galaxy. Indicated RA and Dec are in J2000. The north to the top, and the east to the left.

(a) NGC 4192:

- (tl) DSS b-band $5' \times 5'$; $i = 74^\circ$; $PA = 155^\circ$
- (bl) Ico: $1' \times 1'$; $cl=20 \times (1, 2, \dots, 10, 12, \dots, 16, 18) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 3''$, $PA = 155^\circ$; $cl=0.1 \times (1, 2, \dots, 10, 12, \dots, 22) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=-400$ to 50 , every 50 km s^{-1} .
- (b) NGC 4212: (tl) DSS b-band $5' \times 5'$; $i = 47^\circ$; $PA = 75^\circ$
- (bl) Ico: $1' \times 1'$; $cl=50 \times (0.5, 1, 2, 3, \dots, 10) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 3''$, $PA = 75^\circ$; $cl=0.5 \times (0.25, 1, 2, \dots, 10) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=-200$ to 40 , every 20 km s^{-1} .

(c) NGC 4254:

- (tl) DSS b-band $5' \times 5'$, $i=42^\circ$, $PA=45^\circ$
- (bl) Ico: $80'' \times 80''$; $cl=10 \times (1, 2, \dots, 12) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 3''$, $PA = 45^\circ$; $cl=0.132 \times (1, 2, \dots, 12) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=2300$ to 2530 , every 20 km s^{-1} .

(d) NGC 4303:

- (tl) DSS b-band $5' \times 5'$, $i=25^\circ$, $PA=0^\circ$
- (bl) Ico: $1' \times 1'$; Beam $2''.80 \times 1''.90$; $cl=25 \times (1, 2, \dots, 12) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 3''$, $PA = 340^\circ$; $cl=0.5 \times (1, 2, \dots, 12) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=1500$ to 1600 , every 10 km s^{-1} .

(e) NGC 4402:

- (tl) DSS b-band $5' \times 5'$; $i = 75^\circ$; $PA = 90^\circ$
- (bl) Ico: $80'' \times 80''$; $cl=20 \times (1, 2, 3, \dots, 10) \text{ K km s}^{-1}$.
- (tr) PVD: $80' \times 3''$, $PA = 90^\circ$; $cl=0.3 \times (1, 2, \dots, 12) \text{ K}$.
- (br) V-field: $80'' \times 80''$; $cl=60$ to 340 , every 20 km s^{-1} .

(f) NGC 4419:

- (tl) DSS b-band $5' \times 5'$; $i = 67^\circ$; $PA = 133^\circ$
- (bl) Ico: $1' \times 1'$; $cl=50 \times (0.4, 0.8, 1.2, 2, 3, \dots, 12) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 5''$, $PA = 133^\circ$; $cl=0.5 \times (0.5, 1, 2, \dots, 10) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=-400$ to 0 , every 20 km s^{-1} .

(g) NGC 4501:

- (tl) DSS b-band $5' \times 5'$; $i = 58^\circ$; $PA = 140^\circ$

- (bl) Ico: $80'' \times 80''$; $cl=10 \times (0.5, 1.0, 1.5, 2, 3, \dots, 10, 12, \dots, 20) \text{ K km s}^{-1}$.

- (tr) PVD: $1' \times 10''$, $PA = 140^\circ$; $cl=0.1 \times (0.5, 1, 2, \dots, 10) \text{ K}$.

- (br) V-field: $80'' \times 80''$; $cl=200$ to 500 , every 50 km s^{-1} .

(h) NGC 4535:

- (tl) DSS b-band $5' \times 5'$, $i=43^\circ$, $PA=0^\circ$
- (bl) Ico: $1' \times 1'$; Beam $2''.80 \times 1''.90$; $cl=10 \times (1, 2, 4, 6, \dots, 10, 15, 20, 25) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 10''$, $PA = 0^\circ$; $cl=0.5 \times (1, 2, \dots, 12) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=1800$ to 2100 , every 10 km s^{-1} .

(i) NGC 4536:

- (tl) DSS b-band $5' \times 5'$; $i = 67^\circ$; $PA = 116^\circ$
- (bl) Ico: $1' \times 1'$; $cl=20 \times (1, 2, 4, 6, \dots, 10, 15, 20, 25, 30) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 5''$, $PA = 116^\circ$; $cl=0.5 \times (0.25, 1, 2, \dots, 10) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=1600$ to 2000 , every 50 km s^{-1} .

- (j) NGC 4548: (tl) DSS b-band $5' \times 5'$; $i = 37^\circ$; $PA = 150^\circ$

- (bl) Ico: $1' \times 1'$; $cl=10 \times (1, 2, 3, \dots, 12) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 5''$, $PA = 150^\circ$; $cl=0.15 \times (1, 2, \dots, 10) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=300$ to 700 , every 50 km s^{-1} .

(k) NGC 4569:

- (tl) DSS b-band $5' \times 5'$; $i = 63^\circ$; $PA = 23^\circ$
- (bl) Ico: $1' \times 1'$; $cl=50 \times (0.25, 0.5, 1, 2, \dots, 12) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 5''$, $PA = 160^\circ$; $cl=0.2 \times (1, 2, \dots, 15) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=-380$ to 0 , every 20 km/s .

(l) NGC 4579:

- (tl) DSS b-band $5' \times 5'$; $i = 37^\circ$; $PA = 60^\circ$
- (bl) Ico: $1' \times 1'$; $cl=20 \times (1, 2, 3, \dots, 7) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 5''$, $PA = 90^\circ$; $cl=0.25 \times (1, 2, \dots, 6) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=1320$ to 1600 , every 20 km s^{-1} .

(m) NGC 4654:

- (tl) DSS b-band $5' \times 5'$; $i = 51^\circ$; $PA = 128^\circ$
- (bl) Ico: $1' \times 1'$; $cl=5 \times (1, 2, \dots, 10) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 3''$, $PA = 128^\circ$; $cl=0.1 \times (1, 2, \dots, 10) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=960$ to 1120 , every 20 km s^{-1} .

(n) NGC 4689:

- (tl) DSS b-band $5' \times 5'$; $i = 30^\circ$; $PA = 160^\circ$
- (bl) Ico: $1' \times 1'$; $cl=2.5 \times (1, 2, 3, \dots, 10) \text{ K km s}^{-1}$.
- (tr) PVD: $1' \times 5''$, $PA = 160^\circ$; $cl=0.05 \times (1, 2, \dots, 10) \text{ K}$.
- (br) V-field: $1' \times 1'$; $cl=1500$ to 1700 , every 20 km s^{-1} .

Fig. 2. Integrated $^{12}\text{CO}(J=1-0)$ -intensity maps of the observed galaxies in the same angular scale. The image sizes are $1''.0 \times 1''.0$, or $4.68 \text{ kpc} \times 4.68 \text{ kpc}$ for

an assumed distance of 16.1 Mpc. The contours are drawn at 5, 10, 20, 40, 80, 160 K km s⁻¹.

Fig. 3. CO line velocity fields of the observed galaxies in the same angular scale corresponding to figure 2. Contours are drawn every 20 km s⁻¹ relative to the systemic velocity, which is expressed by white thick contours. Darker coding represents redshift, and white for blueshift.

Fig. 4. Sky plot of I_{CO} on the Virgo Cluster area. Each map is enlarged by 50 times the real angular size. The position of M87 is marked by a cross.

Fig. 5. Radial profiles of the face-on CO intensity obtained by ellipse fitting. The plotted radius is 40''. The primary-beam attenuation has been corrected.

Fig. 6. CO intensity distributions in the central 20'' × 20'' regions of the "central/single-peak" galaxies. Contour levels are 20 × (1, 2, ..., 10, 12, ... 20, 25, ... 40) K km s⁻¹.

Appendix

We show the channel maps of individual galaxies in Figure A1, particularly to confirm that no significant continuum emission has been detected.

Fig. A1. Channel maps of the ¹²CO ($J = 1 - 0$) line emission of the Virgo galaxies. Intensity scale is in Kelvin of brightness temperature. Contours are drawn at 2ⁿ times the lowest-contour value ($n = 1, 2, 3, \dots$). The lowest contour level (cl) is indicated for individual galaxies.

NGC 4192: Lowest cl = 0.5 K.

NGC 4212: Lowest cl = 0.25 K.

NGC 4254: Lowest cl = 0.5 K.

NGC 4303: Lowest cl = 1.0 K.

NGC 4402: Lowest cl = 0.5 K.

NGC 4419: Lowest cl = 0.5 K.

NGC 4501: Lowest cl = 0.20 K.

NGC 4535: Lowest cl = 0.5 K.

NGC 4536: Lowest cl = 0.5 K.

NGC 4548: Lowest cl = 0.25 K.

NGC 4569: Lowest cl = 0.5 K.

NGC 4579: Lowest cl = 1.0 K.

NGC 4654: Lowest cl = 0.5 K.

NGC 4689: Lowest cl = 0.125 K.